EOS Project Calibration Plan

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1.0 Introduction and Background:

The Earth Observing System (EOS) is an 18 year international multi-satellite program in global remote sensing of the Earth. As such, EOS will be the fundamental source of satellite data on the Earth and its environment into the next century. The overall goal of the EOS mission is to advance the scientific understanding of the entire Earth system and its changes on a global scale through the development of a deeper understanding of the components of that system and the interactions among them. In order to achieve the EOS goal of understanding the Earth as a natural system, EOS will produce global, long time series, remote sensing data of the Earth from multiple instruments. As an example, climatic and environmental studies of the long term effects of human activities on the Earth system require remote sensing data that accurately reflect the long term global trends under study. The research resulting from understanding and correctly interpreting these long term data requires the ability to discriminate between on-orbit changes in the satellite instruments and changes in the physical processes of the Earth being monitored. The ability to make this discrimination on a pre-launch and post-launch basis crucially depends (1) on the calibration of the instruments with respect to a set of recognized physical standard sources or processes and (2) on the careful characterization of the instruments' performance at the subsystem and system level. The multi-instrument nature of EOS underscores the need for relating the instruments' measurements through a common set of physical standards or processes. This effectively eliminates the biases between instrument data sets and enables the data from several instruments to be confidently used in Earth remote sensing research.

This document describes the EOS Calibration Plan. It identifies the specific EOS project calibration requirements and goals and outlines an approach toward meeting them.

2.0 Calibration Requirements in EOS:

Requirements for instrument calibration and level 1B (i.e. calibrated and geolocated) data validation, also known as vicarious calibration, are established for the EOS mission to achieve individual mission objectives for the various instruments and for the interdisciplinary investigations. To achieve these mission objectives, the acquisition of data suitable for quantitative analysis that are traceable (i.e. comparable) over at least a decade is required. It is imperative that the prime instrument observations must be related to established standards and standard processes.

Instrument calibration and characterization requirements for the EOS mission have been defined in the EOS 1A Requirements Document [1]. The requirements are listed below.

1. Calibration shall be in terms of physical standards and standard processes.

2. Cross-calibration and comparison of sensors shall be performed both before launch and on-orbit.

3. The principal investigator (PI) or team leader (TL) shall be responsible for calibration. The PI or TL shall

designate one member of the investigation or instrument team (i.e. the Instrument Calibration Representative) as responsible for detailed interface with the EOS Calibration Scientist on calibration and level 1B data validation matters.

4. Instrument calibration reviews shall be performed by peer calibration expert panels comprised of scientists and engineers.

5. Calibration and test fixture design, calibration procedures, and calibration data and analysis documentation shall be deliverable items.

6. Pre-launch calibration and characterization tests, with procedures, shall realistically represent the manner in which the instrument is to operate on-orbit.

7. Mathematical (analytical) models of the behavior of various critical components of the instrument design shall be deliverable items.

8. Level 1B data validation, also known as vicarious calibration, shall occur throughout the lifetime of a measurement series.

9. More than one calibration and vicarious calibration approach shall be used to verify derived data products. These approaches will include ground sites, additional research measurements, measurements from other spacecraft, and measurements from space shuttle missions.

10. Where applicable, preflight calibration and postflight

vicarious calibration must be compared using the same standard calibration scales.

3.0 EOS Calibration Organization:

As shown in the organizational chart of figure 1, the EOS Project Science Office has established the position of EOS Calibration Scientist in the EOS Project Science Office as the single point of contact for EOS calibration issues. The EOS Calibration Scientist performs the following functions:

-provides direct support on calibration issues to the EOS Senior Project Scientist and to the EOS Platform Scientists;

-reports directly to the EOS Senior Project Scientist;

-interacts directly with the EOS calibration community (ie. the individual EOS Instrument Calibration Scientists and EOS Vicarious Calibration Scientists) on EOS calibration issues;

-coordinates periodic meetings of the EOS Calibration Panel;

-coordinates EOS instrument calibration peer reviews;

-constitutes the primary EOS interface with the National Institute of Standards and Technology (NIST) and acts as the technical monitor for NIST calibration support in the EOS project;

-constitutes the technical EOS interface with the United States Geological Survey (USGS) and Northern Arizona University (NAU) on the lunar radiometric measurement program.

EOS instruments and instruments used in the vicarious calibration of the EOS instruments are required to identify a single point of contact for calibration. This person is designated the EOS Instrument Calibration Scientist or the EOS Vicarious Calibration Scientist. This person acts as the specific point of contact for the EOS Calibration Scientist and ultimately the EOS Project Science Office on calibration and level 1B data validation matters.

4.0 EOS Calibration Implementation:

In order to meet the EOS mission calibration requirements, EOS Calibration at the project level is a program involving the participation in a number of efforts by the EOS Calibration Scientist and calibration representatives from EOS instruments and vicarious calibration instruments. The EOS Calibration efforts include the following:

-the formulation of Instrument Calibration Plans by the EOS Instrument Investigation Teams;

-the review of the Instrument Calibration Plans by a panel composed of calibration peers (i.e. Calibration Peer Reviews);

-the participation of the EOS calibration community in meetings of the EOS Calibration Panel;

-the hands-on participation of EOS instrument calibration and vicarious calibration representatives in a number of cross-calibration measurement campaigns and artifact round-robin measurement programs;

-the participation of vicarious calibration representatives in EOS-wide joint field campaigns;

-the participation of the EOS calibration community in calibration workshops.

4.1 EOS Instrument Calibration and Characterization:

The production of the level 1 data product from EOS instruments requires implementation of a calibration phase in which the digital count output of the instrument is converted using calibration coefficients into physically meaningful quantities sensed at the instrument input aperture (e.g. radiance). Instrument calibration is performed pre-flight and post-launch. Pre-flight, radiometric calibration typically uses the instrument under calibration viewing a laboratory source whose output has been characterized relative to a radiance or irradiance scale maintained by a national standards laboratory. Pre-flight calibration is also performed on the instrument on-board radiometric calibration devices using the same standard scales. Pre-flight calibrations should be performed under environmental conditions which closely simulate on-orbit conditions. Post-launch radiometric calibration is performed using the on-board calibration devices and using vicarious targets whose radiant output is simultaneously or near-simultaneously measured by ground and aircraft based instruments. Vicarious targets may include regions of the Earth or the Moon.

Calibration througout the EOS project is in Systeme Internationale (SI) units as recognized by the international scientific community. The use of SI units in EOS calibration permits the interchangeble use of EOS data sets in any physical model and facilitates the comparison of EOS results with results from other satellite-based or ground-based measurement programs. In addition, the reporting of data in SI units provides a natural and consistent mechanism to account for differences in responsivity among EOS instruments and changes in responsivity as instruments age in the space environment.

EOS Instrument characterization with respect to calibration involves measuring pre-launch and possibly post-launch the response of the instrument subsystems and systems to controlled, well-characterized stimuli. As in calibration, instrument characterization should be performed under environmental conditions which simulate on-orbit conditions as closely as possible. Instrument characterization enables the determination of the quantitiative effect of the performance of the subsystems on the overall instrument system level performance. Examples of subsystem level EOS instrument characterization includes the determination of optical filter relative spectral responses with wavelength and the light scattering properties of optical elements, such as mirrors, lenses, and dichroics. Examples of system level instrument characterization includes the determination of the instrument field of view and modulation transfer function (MTF). Characterization must also be extended to the instrumentation and sources used to calibrate the EOS instruments.

EOS Instrument calibration and characterization is monitored by the calibration arm of the EOS Project Science Office in three ways. The first is through the Instrument Calibration Plans and Level 1B Algorithm Theoretical Basis Documents (ATBDs) submitted by the Instrument Investigation Teams to the EOS Project. The second is through the Calibration Peer Reviews, in which the Instrument Calibration Plans are examined, and through the Level 1B ATBD reviews. The third monitoring process is through periodic meetings of the Calibration Panel. Instrument Calibration Plans and Calibration ATBDs, Calibration Peer Reviews, and the Calibration Panel are discussed in Sections 4.1.1, 4.1.2, and 4.1.3, respectively.

4.1.1 Instrument Calibration Plans and Calibration Algorithm Theoretical Basis Documents:

Calibration Plans are initially required from EOS Instrument Investigation Teams at the time of instrument proposal. These plans are periodically refined during instrument development, specifically at the times of the instrument preliminary and critical design stages. In the EOS Background Information Package (BIP) Announcement of Opportunity No. OSSA-1-88 Part One: Guideline for Proposal Preparation [2], a Calibration Plan is required as part of the EOS instrument proposal; and a Calibration Management Plan is required during the instrument definition phase. For many EOS instruments, the instrument calibration plan and calibration manangement plan are combined into a single document, referred to as the Instrument Calibration Plan. The Instrument Calibration Plan should be updated at the time of the

Instrument Engineering Preliminary Design Review (PDR) and again at the time of the Instrument Engineering Critical Design Review (CDR). The version of the instrument calibration plan at the time of the CDR should be a final, mature version of the plan. The Instrument Calibration Plans generated at the time of the PDR and CDR are the subjects of the Calibration Peer Reviews. These reviews are discussed in Section 4.1.2.

At the aforementioned designated times during the development of the EOS instruments, each EOS Instrument Investigation Team is required to generate an up-to-date Instrument Calibration Plan. It is the responsibility of the Instrument Team Leader to deliver the plan to the EOS Calibration Scientist in the EOS Project Science Office. The plan describes the approaches that the Instrument Investigation Team will use to produce their calibrated, level 1B data. These approaches include a description of the test program used to calibrate and characterize the instrument before launch and to monitor the calibration and characterization of the instrument after launch. The Instrument Calibration Plan provides an error budget reflecting how the required calibration accuracy and precision specifications are met. The Instrument Calibration Plan describes how calibration traceability in Systeme Internationale (SI) units to instruments' respective national standards laboratories (e.g. the National Institute for Standards and Technology (NIST-USA), the National Research Laboratory of Metrology (NRLM-Japan), National Research Council-Institute for National Measurement Standards (NRC-INMS-

Canada), National Physical Laboratory (NPL-UK),) will be established and maintained. In addition, the Instrument Calibration Plan includes a description of the algorithms which are used to produce the level 1B data product. The plan includes a description of the techniques which will be used to include ancillary data such as ground truth, vicarious measurements. The plan will also outline the strategy for making comparisons with data sets obtained from other space-based instruments.

In instances where the instrument is being built by private industry under a contract, the instrument builder may provide the Instrument Calibration Plan. However, it remains the responsibility of the Instrument Team Leader (1) to see that the instrument builder produces this plan and (2) to ensure that the plan is delivered to the EOS Calibration Scientist in the Project Science Office.

In January 1993 the EOS Project Science Office requested that instrument teams produce a document describing in detail the algorithms used in the production of their data products. The document describing the algorithms used in the transformation of an instrument's raw, level 0 data to calibrated, level 1B data is the Level 1B Algorithm Theoretical Basis Document (ATBD) for that instrument. Instrument Calibration ATBDs are reviewed by a panel assembled by the EOS Project Scientist through the auspices of the EOS Project Science Office. The EOS Calibration Scientist provides support to the EOS Project Scientist in these reviews.

4.1.2 Calibration Peer Reviews:

A two step procedure has been adopted for peer review of EOS Instrument Calibration Plans. In the first step, the Instrument Calibration Plans are distributed to a peer panel of calibration scientists and engineers for an initial letter review. Members of the peer review panel may include other instrument calibration representatives, members of the Calibration Panel (see section 4.1.3), members of the science team of the instrument under review, and representatives from national standards laboratories. Completed letter reviews are received by the EOS Calibration Scientist and distributed to the Instrument Calibration Representatives. In the second step, a one day panel peer review of the Instrument Calibration Plan and the letter reviews is held preferably at GSFC or possibly at the instrument calibration facility. In this panel review, the EOS Instrument Investigation Team presents an overview of the pre-launch and post-launch calibration and characterization of their instrument to the peer review panel while addressing the specific issues raised in the letter reviews. These panel reviews are chaired by the EOS Calibration Scientist, and are hosted by the individual Instrument Calibration Representatives, if the review is held at the instrument team facility. If the review is held at GSFC, the review is hosted by the EOS Calibration Scientist. The specific time and place for the panel review is determined through negotiations between the EOS Calibration Scientist and the Instrument Calibration Representative.

Ideally, the versions of the instrument calibration plans generated at the times of the instrument PDR and CDR are reviewed. As a minimum requirement, the final version of the instrument calibration plan generated at the time of the CDR will be peer-reviewed.

Details on the format for the Calibration Peer Reviews and the mechanism for the exchange of information between the panel members and instrument team members is presented in Appendix A.

4.1.3 Calibration Panel:

The EOS Calibration Panel provides technical overview for domestic and international instruments on all EOS platforms. The technical scope of the panel includes the following:

-pre-flight and on-orbit instrument calibration and cross-calibration,

-validation of instrument level 1B data products using in-situ and field measurements, and

-ensuring long term stability of the instrument level 1B data products.

The roles and responsibilites of the EOS Calibration Panel with respect to the EOS Project includes the following:

-acting in advisory and review roles to the EOS Calibration Scientist on the formulation of specific EOS calibration programs and documentation,

-informing the EOS Calibration Scientist and the EOS Project Science Office of EOS instrument calibration needs,

-participating with the EOS Calibration and Validation

Scientists in the implementation of a multi-instrument, level 1B project data validation campaigns,

-assessing the progress of the EOS Calibration Scientist in meeting the science objectives of the EOS project with respect to the level 1B data product.

The EOS Calibration Panel is scheduled by the EOS Calibration Scientist to meet once a year. Meetings will be coordinated and chaired by the EOS Calibration Scientist. Membership in the EOS Calibration Panel includes the EOS Calibration Scientist, Instrument Calibration Representatives, Instrument principal investigators (PIs), instrument builder representatives, representatives from national standards laboratories, and invited members from the remote sensing calibration community.

4.2 EOS Instrument Cross-Calibration:

Cross-calibration of EOS instruments is critical to the success the the EOS mission. Only by performing comprehensive and thorough cross-calibration is it possible for the EOS program to generate long-term, continuous, consistent data sets with validity and reliability acceptable to the scientific community for global change research.

Cross-calibration in EOS is performed on many levels both pre-launch and post-launch throughout the 18 year EOS mission. Pre-launch and post-launch cross-calibration includes the EOS instruments, the vicarious calibration instruments, and, in the case of optical sensors, the instruments used to make ground based lunar radiometric measurements. Pre-launch cross-calibration ensures that the instrument calibrations performed by the instrument builders are consistent across all instruments. Inclusion of vicarious calibration instruments in the pre-launch cross-calibration ties the standard scales of the level 1B data validation instruments to a common EOS instrument scale. Post-launch cross-calibration is essential for many reasons. Post-launch cross-calibration ensures that the level 1B data from EOS instruments yield consistent higher order products. Post-launch calibration reduces the amount of post-launch research, analysis, and processing needed before the scientific use of the level 1B products. Lastly, post-launch calibration reduces the probability of needing to correct higher order data products derived from poorly calibrated level 1B data. Continuation of the post-launch cross-calibration of the vicarious calibration instruments, the ground-based lunar radiometric instruments, and the EOS instruments on future platforms ensures that validated level 1B data from the orbiting platform and calibrated/validated level 1B data from future platforms will share a common, standard scale.

4.2.1 Pre-launch Cross-Calibration:

The goals of pre-launch, laboratory-based cross-calibration in EOS are twofold. The first goal is to validate, pre-flight, the independent scales assigned to the sources used in the actual calibration of the EOS instruments against the scales maintained by a national standards laboratory. The second goal is to make a simultaneous, direct comparison of measurements made by the EOS instruments, vicarious calibration instruments, EOS secondary standards facilities, and national standards laboratories. Accomplishing the first and second goals ensures the distribution of a common scale in Systeme Internationale (SI) units at the EOS instrument calibration facilities, the EOS secondary standards facilities, and the vicarious instrument calibration facilities. A third goal of pre-launch laboratory-based cross-calibration is to evaluate the measurement results in terms of measurement procedure and basic metrology.

As an example, in the case of the AM-1 instruments, pre-launch cross-calibation involves calibrating all the sources used to radiometrically calibrate the AM-1 instruments (e.g. integrating spheres and blackbodies). The accuracy of these AM-1 instrument source calibrations must exceed the radiometric calibration accuracy specifications of the EOS instruments.

In order to validate the radiance scales of the sources used in the calibration of the EOS AM-1 instruments and to compare the radiance measurements of EOS AM-1 instruments, secondary standard and vicarious calibration groups with measurements made by NIST, a series of transfer radiometers has been independently developed by several metrology laboratories. These radiometers make simultaneous radiance measurements of the sources used to calibrate the EOS AM-1 instruments. In order to accomplish this task, the EOS Project Science Office has enlisted the expertise of the NIST Optical Technology Division in designing, fabricating, and fully characterizing a set of three EOS transfer radiometers spanning the visible to thermal infrared wavelength region. The design for the visible and shortwave infrared radiometers closely follows the NIST design of the SeaWiFS transfer radiometer (SXRs) [3]. The thermal infrared radiometer, which required a significant study phase before design and fabrication, has been breadboarded and is currently being tested [4]. These radiometers view the radiance calibration sources at EOS instrument builder facilities and the lunar radiance measurement facility and transfer a common radiometric scale to these sources that is traceable to a NIST radiometric standard. Visible/near infrared and shortwave infrared transfer radiometers have been designed, fabricated, and tested by the University of Arizona Optical Sciences Center Remote Sensing Group. In addition to verifying the radiometric scales of EOS instrument radiance and lunar radiometric calibration sources, the University of Arizona radiometers are used to transfer the EOS standard radiometric scale to their ground-based vicarious calibration radiometers [5]. The National Research Laboratory of Metrology (NRLM) in Japan has fabricated a set of visible/near infrared and shortwave infrared radiometers. The NRLM radiometers are used in the calibration of the integrating sphere source used to calibrate the EOS ASTER instrument [6]. While the EOS/NIST, NRLM, and University of Arizona radiometers are discrete filter instruments, the NASA/GSFC Code 920.1 Space Geodesy Networks and Sensor Calibration Office provides a scanning spectroradiometer to the EOS Radiometric Measurement Program. The NASA/GSFC instrumentation measures the irradiance of the source under test over the wavelength range from 0.4 to 2.5 microns and compares this irradiance to that measured from NIST irradiance standard lamps. By folding the appropriate aperture diameters and distances into the calculation, the radiance of the source under test is determined [7,8]. The NASA/GSFC equipment provides valuable information on the shape of the radiance versus wavelength curve in the visible and shortwave infrared regions.

The aforementioned radiometers and radiometers used by the EOS instrument builders to measure their radiance calibration sources are the current participants in the EOS AM-1 Radiometric Measurement Comparison program. It is hoped that expansion of this cross-calibration activity to include radiometers used in the calibration of other Mission to Planet Earth (MTPE) sensors, vicarious calibration instrumentation, and international sensors will be possible in the future. In order to accomodate larger participation and not over-burden the EOS instrument calibration facilities, clean, secondary standards laboratories housing stable radiance standards from the visible through the thermal infrared are needed. A detailed plan for the EOS Radiometric Measurement Comparison is outlined in Appendix B.

In the EOS Project Calibration Management Plan generated in January 1990, pre-flight instrument cross-calibration was to be performed not only at the instrument builder facilities, but also at the platform integration facility [9]. The plan for cross-calibration at the platform integration facility was greatly modified as a result of discussions between attendees of the sixth meeting of the Calibration Advisory Panel in San Diego, in January 1993 [10]. In that meeting, EOS instrument calibration activities were prioritized in the following order of decreasing importance:

-individual instrument calibration as planned by the individual instrument teams;

-in-flight radiometric and geometric cross-calibration using suitable Earth targets; and round-robin cross-calibration activities done in the instrument builder facilities;

-cross-calibration done at the platform integration site.

Since the time of that meeting and for reasons of excessive cost, difficulties in schedule, and questionable calibration benefit, cross-calibration at the platform integration site was refined. Instrument teams may bring sources and equipment to the platform integration facility for purposes of performing bench acceptance testing and ensuring instrument calibration has not changed. The nature of the sources, accompanying equipment, and planned tests are communicated to and/or negotiated with the appropriate EOS Project Office (i.e. AM, PM, Chem, etc.) and the platform integrator well in advance of instrument shipment and platform integration.

4.2.2 Post-launch Cross-Calibration:

EOS cross-calibration activities continue through the launch of the instrument platforms, to ensure measurement traceability and consistency between successive instruments on following platforms. For example, cross-calibration in the post-EOS AM-1 launch timeframe will involve continuing the EOS Radiometric Measurement Comparisons by extending the program to include EOS PM-1 instrument calibration facilities, PM-1 vicarious calibration facilities, and select non-EOS instrument calibration facilities.

In support of the EOS post-launch calibration and cross-calibration of current and future instruments operating in the 0.384nm to 2.5 micron wavelength region, the United States Geological Survey (USGS) and Northern Arizona University, both located in Flagstaff, AZ, are under contract through the EOS

Project Science Office to make long-term radiance measurements of the Moon. The Moon is the only object accessible to all terrestrial orbiting spacecraft that is within the dynamic range of most imaging instruments and is stable enough to provide a calibration target. The EOS/NIST and University of Arizona radiometers will continue to be used through the duration of the lunar radiometric measurement program to transfer the EOS standard radiometric scale to the lunar radiance measurement calibration equipment. Details of this lunar radiance measurement program are found in a number of publications [11, 12].

4.3 EOS Vicarious Calibration Joint Field Campaigns:

The EOS Calibration Scientist, in cooperation with the EOS Validation Scientist, assists domestic and international vicarious calibration groups in promoting and coordinating EOS joint field campaigns in the vicarious calibration (i.e. level 1B data product validation)of EOS sensors. In addition to promoting and coordinating these joint field campaigns, the EOS Validation and Calibration Scientists are continuing the effort started by the Committee on Earth Observing Satellites Working Group on Calibration and Validation (CEOS WGCV) [13]. This goal of this effort is to produce a single international database of reasonably detailed information on calibration and validation capabilities applicable to MPTE and other EOS missions. This information is ultimately used by the EOS Validation and Calibration Scientists in identifying (1) participants for specific EOS vicarious calibration joint field campaigns and (2) field sites.

The coordination of vicarious calibration field campaigns improves the overall quality of the vicarious calibration data and thereby improves the quality of the EOS instruments' level 1B data product. This coordination results in a wiser use of EOS mission resources. In order to be effective, coordinated vicarious field campaigns must begin in the pre-launch timeframe and must be of sufficient length and frequency to produce from each participant a representative long time series data set. Well coordinated joint field campaigns are the definitive method in determining the measurement uncertainties of the vicarious calibration techniques. A knowledge of these measurement uncertainties is absolutely necessary if vicarious calibration data is to be integrated with other calibration data to improve the overall level 1B data product.

4.4 EOS Artifact Measurement Round-Robins:

In addition to the EOS Radiometric Measurement Comparison Program and the EOS Vicarious Calibration Joint Field Campaigns, the EOS Project and NIST coordinate and oversee calibration and/or radiometric artifact round-robins. As an example of these artifact round-robins, Appendix C presents the detailed plan for the EOS Bidirectional Reflectance Distribution Function (BRDF)/Bidirectional Reflectance Function (BRF) Diffuse Reflectance Round-robin which is in support of EOS AM-1 instruments flying on-board solar diffusers.

Additional candidate round-robin programs may be identified by members of the EOS calibration community, presented at EOS Calibration Panel meetings, and brought to the attention of the EOS Calibration Scientist in the form of a well-conceived measurement comparison plan. Examples of candidate programs include round-robin measurement programs in dimensional metrology (e.g. aperture area) and spectrophotometry (e.g. filter transmittance). In all cases, EOS artifact round-robins will serve to corroborate the measurement practices, instrumentation, and capability of EOS -related efforts at the various laboratories and commercial facilities. In general, they will not be simultaneous with calibration and characterization of flight hardware.

4.5 EOS Calibration Workshops:

Results from EOS calibration programs such as the EOS Radiometric Measurement Comparison and the Artifact Measurement Round-robins in combination with input from EOS instrument calibration and vicarious calibration representatives will be used to assess the need for calibration workshops. Workshops will primarily be designed to be responsive to specific radiometric measurement problems experienced or anticipated by the EOS Calibration Community. Workshops will be separated by the classic wavelength disciplines of visible/near infrared/short wave infrared, thermal infrared, and microwave. The workshop activities may include presentations of the state-of-the-art in instrument calibration and characterization, demonstrations of good radiometric/calibration technique followed possibly by hands-on applications, and review of cross-calibration and artifact round-robin measurement techniques and results.

Appendix A: Recommended Format and Information Exchange Protocol for the EOS Instrument Calibration Peer Reviews

A two step procedure has been adopted for the peer review of EOS Instrument Calibration Plans. This two step procedure is a departure from the original approach to peer reviewing calibration plans. In the first step of the two step procedure, the Instrument Calibration Plans prepared by the Instrument Calibration Representative with the aid of the Instrument Investigation Team are distributed by the EOS Calibration Scientist to a peer panel of calibration scientists and engineers for an initial letter review. Members of the peer review panel are selected by the EOS Calibration Scientist and may include calibration representatives from other instruments, members of the Calibration Panel, members of the science team of the instrument under review, and representatives from national standards laboratories. One month after distribution of the calibration plans, completed letter reviews are received by the EOS Calibration Scientist from the panel members and are distributed to the Instrument Calibration Representative.

In the second step, a one day panel peer review of the Instrument Calibration Plan and the letter reviews is held preferably at GSFC or possibly at the instrument calibration facility. The exact time and place for this panel review will be negotiated and scheduled by the Instrument Calibration Representative and the EOS Calibration Scientist. In the panel review, the EOS Instrument Investigation Team presents an overview of the pre-launch and post-launch calibration and characterization of their instrument while addressing the specific issues raised in the letter reviews. The panel reviews are chaired by the EOS Calibration Scientist and are hosted by the EOS Calibration Scientist for reviews held at GSFC and by the Instrument Calibration Representative for reviews held at the instrument calibration facility.

The following format presents several topics and a strawman format for the EOS Calibration Peer Panel Reviews:

1. Welcome and Introductions:

-Welcome by EOS Calibration Scientist acting as the chair of the Calibration Peer Review

-Self-introduction of panel members, key program participants from the instruments, and review attendees

2. Instrument Investigation Objectives:

-Presentation of scientific goals, science products, wavelength regions, level 1 product accuracy requirements and how these requirements relate to level 2 product accuracy requirements

-Presentation of instrument product similarities and differences from related EOS and non-EOS instruments

3. Instrument Description:

-Description of the basic instrument design and operation and how that design will obtain the required data products and achieve the science goals

-Outline of instrument design differences and similarities to related or heritage instruments

4. Overall Calibration Approach and Error Budget:

-Presentation of the overall instrument calibration strategy and associated error budget

-Description of pre-flight instrument calibration

-Description of in-flight, on-board instrument calibration

-Description of how pre-flight calibration is transferred to the on-board calibrators and how that calibration is maintained through launch and on-orbit

-Description of post-launch vicarious calibration including calibrations requiring spacecraft maneuvers

-Description of all pre-launch and post-launch characterization tests to be performed on the instrument, the testing methodology, how these tests meet the accuracy and precision requirements,and the associated error budgets for these tests

-Description of how the overall calibration establishes and maintains a traceability to calibration standards maintained by national standards laboratories

5. Detailed Calibration Approach and Error Budget:

-Presentation of detailed error budget for pre-flight on-board, in-flight on-board, and post- launch vicarious calibration, including a description of how each budgeted value is obtained and how each error contributes to the overall error

-Presentation of radiometric models and algorithms used in the determination of the calibration error budgets

-Detailed description of instrument tests and methods and application of calibration to these tests and methods

6. Tour of Instrumental Radiometric Calibration Facilities (if peer review is held at instrument calibration facility)

7. Review Panel Internal Discussions

8. Review Panel Briefing to Instrument Team

During the calibration peer panel review, review panel members are encouraged to raise instrument calibration and characterization related questions directed to the presenter and other members of the instrument team. In addition, questioning review panel members must provide written comments, questions, and recommendations using a form identified as an Information Request Form. Copies of the completed Information Request forms will be provided to the Instrument Calibration Representative by the panel chairperson within two weeks of the review. A draft report, including a recommended priority for addressing the Information

Requests, is provided to the Instrument Calibration Representative by the EOS Calibration Scientist within one month of the review. The Calibration Peer Review panel expects a response to each Information Request through the Instrument Calibration Representative. For those information requests requiring a response from an instrument builder under contract, the acquisition of a response is negotiated between the EOS Project and the Instrument Manager. A final, formal review report, including responses to each Information Request, is provided to the instrument team within three months of the review. The final review report is also sent to each review panel member.

Appendix B. EOS Radiometric Measurement Comparison Program:

I. Program Objectives:

The most important part of the EOS AM-1 pre-launch cross-calibration program is the EOS Radiometric Measurement Comparison Program. The goal of this program is to circulate groups of radiometers to instrument calibration facilities for purposes of making radiance measurements on the exact sources used in the pre-launch calibration of the EOS instruments. This program will accomplish several important pre-launch calibration tasks. These include the following:

-the validation of the spectral radiance of the calibration sources as calibrated by EOS instrument providers with that determined by a national standards laboratory;

-the comparison of measurements from the radiometers used in vicarious calibration programs in direct support of EOS instruments with simultaneous measurements made by the EOS radiometers;

-the comparison of measurements from radiometers used in the secondary standards calibration of ground-based and airborne instruments in support of EOS level 1B validation with simultaneous measurements made by the EOS radiometers;

-the evaluation of measurement results in terms of measurement procedure and basic metrology.

-the pre-launch identification of any inconsistencies between EOS instrument, vicarious instrument, and secondary standard calibration measurements, techniques, and procedures.

-the placement of instruments on the same platform on the same radiometric scale;

-the placement of the radiance calibration sources of instruments on different platforms on the same radiometric scale.

II. Program Implementation:

The transfer radiometers currently used in the EOS Radiometric Cross-comparison Program have been developed by four facilities. In order to meet the challenging calibration requirements of the EOS instrument radiance calibration sources, the EOS project has contracted with the Optical Technology Division at NIST to produce three filter radiometers operating from roughly 0.4 to 10 microns. The visible and shortwave infrared radiometers will operate in ambient and will be of similar design to the transfer radiometer designed by NIST for the SeaWiFS project [3]. The thermal infrared radiometer has been designed and breadboarded and will operate in thermal vacuum or ambient. These radiometers will serve the dual role in the EOS cross-calibration of (1) making radiance measurements of all EOS radiance calibration sources that can be directly compared, and (2) transferring a standard NIST radiance scale between all EOS instrument calibration facilities. A second set of transfer radiometers operating in the visible and shortwave infrared has been designed and built by the University of Arizona Optical Sciences Center [4]. The participation of this group of radiometers in the cross-comparison program provides an excellent check of the measurements made by the suite of transfer radiometers and extends the standard EOS radiometric scale to the University of Arizona vicarious calibration program. The third set of radiometers has been fabricated by the National Research Laboratory of Metrology (NRLM) in Japan [5]. These radiometers operate in the visible through shortwave infrared and are used in the calibration of the EOS AM-1 ASTER instrument. The participation of the NRLM radiometers not only provides another check of the radiance measurements of the participating radiometers, but also enables a comparison of the NIST radiance scale to that maintained by NRLM in Japan. The fourth radiometer is a scanning monochromator-based system operated by NASA/Goddard Space Flight Center. The NASA/GSFC scanning spectroradiometer measures the irradiance from NIST irradiance standard lamps and transfers that irradiance scale to the radiant source under test. By folding in the geometry of the measurement, the radiance of the source under test is calculated [7,8]. The participation of the NASA/GSFC scanning spectroradiometric system in the program provides a different methodology and approach towards the measurement of radiance and can provide important information on the shape of the radiance versus wavelength curve.

In addition to the four sets of radiometers mentioned above, other participants are selected by the EOS Calibration Scientist in consultation with NIST. The calibration representative from the instrument builder facility hosting the program is automatically invited and encouraged to participate in the measurement comparison. The number of additional participants in a comparison campaign depends on the amount of time and resources available, number of measurements to be made, and any restrictions imposed by the hosting EOS builder's facility. Additional participants may be the calibration representatives from (1) other EOS instruments, (2) selected vicarious calibration programs, (3) the national standards laboratories of non-US EOS instruments, and (4) international non-EOS instrument calibration representatives. Invitations will be extended by the EOS Calibration Scientist to additional participants.

A. Pre-comparison Preparations:

Overall coordination of the comparison is performed by the EOS Calibration Scientist. Before final participant selection, the EOS Calibration Scientist contacts the NASA Instrument Manager for permission to contact the EOS instrument builder's calibration representative. The EOS Instrument Calibration Representative will provide information to the EOS Calibration Scientist shown in the questionnaire that follows.

Pre-comparison Questionaire to Instrument Builder Calibration Representative:

1. What are your proposed dates for the campaign?

2. What total number of people are you willing to accomodate in your facility during the campaign?

3. Would you object to a pre-comparison site visit by the EOS Calibration Scientist or representative?

A. Do you have a video or pictures of the sources to be measured and the area around the sources?

B. Would you object to a video or pictures being taken?

4. Is/are the source/sources to be measured located in a cleanroom?

A. What cleanroom restrictions do you envision for the measurement participants and their equipment?

B. Are the tools for cleaning the participants' equipment available at your facility?

5. What are the dimensions of the room housing the source/sources?

6. What is the color and finish of the ceiling, walls, and floor?

7. Will the lights in the room be able to be turned off during the measurements?

8. What electrical power will be made available to the participants?

A. Number of outlets

B. Voltage, currents, and frequency for each outlet

C. Type of plug for each outlet including grounding convention

9. Will the temperature and humidity record of the room housing the sources be made available to the participants during the time of the campaign?

10. What source/sources will be measured?

Integrating Sphere Sources:

A. For integrating sphere sources, what is shape of the source aperture? What are the precise dimensions of the aperture?

B. What is the distance from the floor to the aperture center? Is this distance adjustable? Over what range can this distance be adjusted?

C. What is the thickness of the source aperture?

D. What is the range of distances from the aperture that measurements can be made?

E. What are the characteristics of the integrating sphere?

1. Number of lamps, lamp voltage, and power

2. Are the voltage and current/power that the sphere lamps are operated during the campaign recorded? Will they be made available to participants?

3. Size of sphere (i.e. inner diameter)

4. Cooling technique

5. Wall coating or material

F. What light levels (in radiance units) would you recommend measurements be made? How are these light levels realized in operating the sphere? What wavelength bands are these light levels associated with?

G. What is your recommended warm-up time for your sphere assuming a cold start? Is there a recommended stablilization time between light level changes? What is that time?

H. Are there any refereed or non-refereed descriptions of this source? What are they?

Blackbody/Thermal Infrared Sources:

A. What is the thermal infrared source type (eg. cavity, concentric groove, etc.)?

B. Could a dimensioned drawing of your source be provided?

C. What are the range of angles over which the source is expected to radiate as a diffuse, Lambertian source?

D. What is the typical operating distance from the source aperture to the EOS sensor?

E. What do you anticipate to be the distance from the source aperture to the entrance aperture of the NIST TIR transfer radiometer, given that the latter is roughly 12 inches in diameter?

F. What temperature range will the source be operated over during EOS instrument calibrations?

G. What is the emissivity of your source? How is this emissivity determined (eg. modelling, etc)?

H. What is the temporal stability of your source?

I. What is the polarization of your source?

J. Will your source be operated in ambient, vacuum, or both? Do you envision the EOS TIR transfer radiometer operating in ambient, vacuum, or both?

K. Could a dimensioned drawing of your vacuum/calibration chamber be obtained?

L. What are the electrical connectors in the vacuum chamber that are available for the TIR transfer radiometer?

M. What are the details on the feedthroughs for the vacuum and liquid nitrogen lines that could be used for the TIR transfer radiometer? The TIR transfer radiometer will need one vacuum line and two nitrogen lines, one for inlet and one for exhaust.

N. The TIR transfer radiometer is anticipated to have a diameter of roughly 12 inches and an overall height of roughly 15 inches including its own translation/rotation stage. Will this fit in your chamber? How large of a radiometer could your vacuum chamber accomodate?

O. What are the design details of any mounting flanges that could be used for mounting the TIR transfer radiometer in the vacuum chamber? This is needed so that an adaptor mounting flange for the TIR transfer radiometer can be made.

P. What is the base pressure in the vacuum chamber under the conditions when the TIR transfer radiometer is used?

R. What is the thermal environment in the vacuum chamber when the TIR transfer radiometer is used? Include all relevant surfaces (eg. 80°K shields, 270°K and variable, etc.).

11. To what address should participants send their equipment? Who is the primary contact for shipping this equipment to your facility? What is that person's phone number, fax number, and e-mail address?

Participants will provide the EOS Calibration Scientist with the information in the following questionaire.

Pre-comparison Questionaire to the Participants

1. What instrumentation are you sending to the campaign? Please send a copy of your shipping document, if possible.

2. What are your electrical power needs for operating your equipment?

3. Do you foresee any need for special equipment, such as an optical table, etc?

4. Does your equipment require a "warm-up" period? What is the length of time for "warming-up"?

5. What is your estimate of the total amount of time it takes for your equipment to make a single radiance measurement at one source radiance level?

6. Is there a paper or writeup describing your equipment, radiance measurement methods or technique, and the accuracy/precision or error in your radiance measurements? Please provide a copy.

B. Cross-comparison Agenda:

A recommended agenda for the Cross-comparison campaigns is presented below.

Agenda for EOS Radiometric Cross-comparison Campaigns

Day 1:

-Welcoming remarks from the EOS Calibration Scientist and the instrument builder facility calibration representative.

-Self introduction of participants

-Agreement on participant order of measurement

-Distribution of measurement log sheets to participants

-Unpacking and cleaning of equipment

Day 2 through Day N:

-Warming up of instruments and source/sources

-Begin radiance measurements

-At end of day, convene at designated meeting room to report and record rapid results and to submit completed measurement log sheets to NIST comparison representative.

-Adjourn

Day N+1:

-Pack equipment

-Convene at designated meeting room to briefly discuss results, to decide on appropriate timeframe (approx. 1 month later) to deliver final results to NIST comparison representative, to decide on publication matters, to decide what meetings these results will be presented, and to submit completed log sheets and electronic copies of raw data files to NIST comparison representative.

-Adjourn

C. Post-comparison activities:

The NIST comparison representative will be the recipient of the final radiance data from each participant. A first draft of a paper or report on the cross-comparison campaign will be completed by the EOS Calibration Scientist and the NIST comparison representative and distributed for comments to all the participants. The results of the campaign will be made available electronically and will be submitted to EOSDIS as a standard data product.

Appendix C. EOS Bidirectional Reflectance Distribution Function (BRDF)/Bidirectional Reflectance Function (BRF) Measurement Round-robin:

I. Introduction:

On the EOS AM-1 platform scheduled for launch in 1998 the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multiangle Imaging Spectroradiometer (MISR) will employ solar illuminated diffuse reflectance targets for in-orbit radiance calibration. In order to effectively use these targets, the bidirectional reflectance distribution function (BRDF) or the bidirectional reflectance function (BRF) of the targets must be measured prelaunch and monitored postlaunch. Prelaunch determination of the BRDF/BRF of these targets relies on goniometric measurements of the target reflected radiance and incident irradiance as a function of the in-flight solar incident and scattered polar and azimuthal angles. For the EOS instruments, these measurements will be made by a number of laboratories.

A BRDF round-robin measurement comparison was conducted using an aluminum disk coated with polyurethane enamel as a white diffuse target [14]. A comparison of BRDF measurements on this sample by 16 participating laboratories at one visible laser wavelength produced a measurement uncertainty range of up to 17% at an incident angle of 10° and at scatter angles from 15° to 70°. These results emphasize the need for a BRDF/BRF comparison between metrology facilities with ties to the EOS program. This document presents a framework for a BRDF measurement comparison between laboratories with either direct or indirect links to the EOS program. The measurement comparison hopefully will establish the initial range of BRDF measurement uncertainty in advance of the launch of the EOS platform.

II. Participating Laboratories:

The following laboratories have been identified as candidates for the BRDF measurement comparison program:

-National Institute for Standards and Technology
 Radiometric Physics Division

-NASA/Goddard Space Flight Center
 Sensor Development and Characterization Branch

-Santa Barbara Research Center

-NASA/Jet Propulsion Laboratory

-University of Arizona
 Optical Sciences Center

III. Approach:

A. Diffuse Targets:

Four candidate targets have been identified for the BRDF/BRF comparison program. These targets include the following:

-1.5 inch diameter pressed halon sample obtained from NIST,

-1.5 inch diameter pressed and scintered halon sample obtained from NIST,

-2.0 inch diameter Spectralon sample obtained from Labsphere,

-1.5 inch diameter roughened aluminum overcoated with aluminum sample.

In order to avoid losing the samples, the samples may be transported by a representative of NASA/GSFC to and from the participating laboratories. The samples will be transported in a compartmentalized Zero box. Sample handling instructions will be provided. In addition fiducial marks on each sample will enable each laboratory to identically position the targets in azimuth before measurements are made.

B. Measurement Wavelengths and Angles:

Anyone who has made BRDF/BRF measurements will attest to the fact that the number of wavelength and angular permutations can quickly balloon to an unmanageable number in BRDF/BRF studies. An effort has been made in restricting the number of measurements to the minimum needed to characterize the BRDF/BRF mesurement offsets of the laboratories. A review of the wavelengths used by the MODIS, MISR, and SeaWiFS instruments produced the following proposed wavelengths at which BRDF/BRF measurements should be made:

443nmn, 550nm, 670nm, 865nm, 940nm, 1240nm, 1640nm, and 2130nm.

A bandwidth of 10nm is recommended for these wavelengths. It is realized that some laboratories may not be interested in making or be able to make BRDF/BRF measurements for all wavelengths and at the suggested bandwidth of 10nm. Those laboratories are requested to make BRDF/BRF measurements at those wavelengths possible. It is also anticipated that BRDF/BRF measurements using a 10nm bandwidth will not differ greatly from measurements using slightly wider bandwidths. It is important, however, that the BRDF/BRF data reported by the laboratories should be for the case of unpolarized scattering.

A review of the incident and viewing angles of the MODIS, MISR, and SeaWiFS instruments produces the following proposed angles at which BRDF/BRF measurements should be made:

Incident polar (elevation) angles: 0°, 15°, 30°, 45°, and 60°

Viewing polar (elevation) angles: -60° to 60° in 10° steps.

The above angles are referenced to the diffuser normal as shown in Figure 1A. Because all laboratories do not have an out-of-plane measurement capability, azimuthal or out-of-plane BRDF/BRF scans will not be requested in this comparison. All requested measurements will be in-plane.

C. Absolute versus Relative Measurements:

Many of the participating laboratories in this comparison make BRDF or BRF measurements relative to a standard or reference sample. For those laboratories which use a standard, reference sample in making BRDF/BRF measurements, it is requested that they provide a write-up outlining their measurement approach detailing their use of any standard samples.

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